Introduction to the special section: Violent Sun-Earth connection events of October–November 2003

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[1] During 2003 October and November, a series of solar eruptions occurred from three solar active regions. Some of these eruptions were extreme in terms of their origin (source properties) and heliospheric consequences. This paper summarizes the first results of the analysis of these violent Sun-Earth connection events. **Citation:** Gopalswamy, N., L. Barbieri, G. Lu, S. P. Plunkett, and R. M. Skoug (2005), Introduction to the special section: Violent Sun-Earth connection events of October–November 2003, *Geophys. Res. Lett.*, *32*, L03S01, doi:10.1029/2005GL022348.

1. Introduction

[2] After a significant lull in its activity, the Sun unleashed a series of eruptions over a three-week period from October 18 to November 7, 2003, from three active regions (ARs) with NOAA numbers 484, 486, and 488, including the largest flare and one of the fastest coronal mass ejection (CME) of solar cycle 23. AR484 returned as AR501 and produced the largest geomagnetic storm of the solar cycle. A series of shocks were launched into the heliosphere, some of them accelerating particles to unprecedented intensities. Earth's ionosphere and atmosphere were severely affected by these eruptions. The impact of these eruptions was felt not only in the near-Earth space environment, but also in the far reaches of the heliosphere: Spacecraft located much beyond Earth's orbit such as Ulysses, Cassini, and the Voyagers felt the shocks from these eruptions. This special section consists of first results that highlight the level of our current understanding on the Sun-Solar system connection based on analysis of the October–November 2003 events. Extensive analyses of these violent Sun-Earth connection events will also be published in *Journal of Geophysical Research-Space Physics* and in *Space Weather*.

2. Solar Genesis

[3] The X17.2 flare of 2003 October 28 was the largest on-disk flare of the 2003 October–November period of interest (the largest flare occurred on November 4, but it was close to the west limb). This flare was associated with an Earth-directed CME and the most intense solar energetic particle (SEP) event of cycle 23, including a ground level event (GLE). *Bieber et al.* [2005] analyze several unusual aspects of this GLE. They conclude that relativistic solar neutrons were emitted from this flare over about 9 minutes, and that the neutron emission began several minutes before the main onset of relativistic protons. Y.-H. Yang et al. (Flare-associated variation of localized magnetic flux in AR 10486 on October 28, 2003, submitted to *Geophysical Research Letters*, 2005) use high-cadence magnetograms obtained with SOHO to investigate variations in the photospheric magnetic field associated with the same flare and CME on October 28. They find both transient and permanent changes in the field at the flare site. *Gopalswamy et al.* [2005] identify the source of the largest geomagnetic storm of the current solar cycle (Dst ~ -472 nT) on November 20 as a CME that erupted on November 18 near the Sun center and evolved into an interplanetary magnetic cloud. The associated active region (AR501) was the return of AR484. They find that the magnetic cloud was highly tilted so that the axial magnetic field had a strong southward component, and they suggest that the intense geomagnetic storm was caused by reconnection of this field with Earth's field.

3. Impact on Spacecraft Mission Operations

[4] About 59% of the reporting spacecraft and about 18% of the instrument groups experienced some effect from the solar activity between mid-October and early November 2003. The types of environmental effects observed on the spacecraft were electronic upsets, housekeeping and science noise, proton degradation to solar arrays, upper atmosphere–induced changes to orbit dynamics, high levels of accumulated radiation, and proton heating. The spacecraft affected are in low-Earth orbit (LEO), Geostationary (GEO) and interplanetary regimes, and carry out Earth science, space science and communications missions. Many of those missions monitor space weather phenomena; their continued operation was vital to the collection of data during the October–November storms. Two important things need to be noted from the impact of the extreme space environment during this period on satellite mission performance and operations:

[5] First, though some instruments failed in ways attributed to the space environment on both a LEO and an interplanetary mission, no spacecraft missions or spacecraft were lost. Operations for on-orbit missions implemented measures to detect the space weather events and took appropriate preventive actions. Some missions turned off their instruments or put them or the spacecraft in a safer operating mode. And the design of on-orbit missions, proved to be compatible with mission goals and risk: spacecraft like ACE that needed to survive the severe environment to provide observations, did.

[6] Second, as so well illustrated by the papers in the special section, the space observations coupled with ground

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based observations provided a wealth of well defined data for a benchmark event. Some of the most intense solar flares measured in 0.1 to 0.8 nm X-rays in recent history occurred and are compared and contrasted to the July 14, 2000, Bastille Day (X10) event using the SOHO SEM 26.0 to 34.0 nm EUV and TIMED SEE 0.1–194 nm data [*Tsurutani et al.*, 2005]. X-ray emission from Jupiter observed by XMM-Newton suggests that Jovian equatorial X-rays can be used to monitor the solar X-ray flare activity on the hemisphere of the Sun that is invisible to space weather satellites [*Bhardwaj et al.*, 2005]; SAMPEX observations report the response of the low-altitude radiation population during and after the strong SEP events and geomagnetic disturbances of late October and early November 2003 and they are placed in the context of observations throughout the 12-year SAMPEX mission. Never before has such a large decrease of the energetic protons at low altitude been observed. An injection of very high energy electrons like this has not been seen since February 1994 [*Looper et al.*, 2005].

4. Near-Earth Consequences

4.1. SEPs and Earth's Atmosphere

[7] The largest SEP event occurred on October 28, 2003, and resulted in a significant ozone depletion due to the production of high levels of HOx constituents in the mesosphere and upper stratosphere [*Degenstein et al.*, 2005]. Ozone depletion was observed by the Canadian Optical Spectrograph and InfraRed Imager System (OSIRIS) across the southern polar cap and extended to latitudes as far north as 45°S. The ozone depletion was observed between 50 and 80 km with a maximum value of 75% around 65 km. Y. J. Orsolini et al. (An upper stratospheric layer of enhanced HNO_3 following exceptional solar storms, submitted to *Geophysical Research Letters*, 2005) reported on an extraordinary, long-lasting, high-altitude HNO3 layer observed by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) instrument in the polar upper stratosphere. The HNO_3-enhanced layer was first seen around 20 November 2003 in the upper stratosphere, and descended to near 30 km by early January 2004. They suggest that particle precipitation from the intense solar storms of October–November 2003 was responsible for this layer.

4.2. Ionospheric and Magnetospheric Responses

[8] Total electron content (TEC) measurements recorded the prompt global ionospheric response to the October 29–30 storms, and up to 250% increase in TEC was observed on October 30 (A. J. Mannaucci et al., Prompt dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 "Halloween Storms," submitted to *Geophysical Research Letters*, 2005). The increase in TEC has been suggested to be the result of the dayside ionospheric uplift caused by prompt penetration of enhanced interplanetary electric field to the low-latitude ionosphere. The similar mechanism has also been suggested as the cause of two storm-enhanced density events observed in the northern hemisphere, which also have conjugate counterparts in the southern hemisphere (C. Coker et al., Conjugate observations of storm-enhanced density, submitted to *Geophysical Research Letters*, 2005). Using observations from the array of North American GPS receivers *Foster and Rideout* [2005] found more than ten times of TEC enhancement over the US mainland during the October 30–31 superstorm, along with sharp TEC gradients on the edge of the enhanced TEC patch. Such storm-enhanced plasma plumes are attributed to the strong subauroral polarization electric fields that erode the outer reaches of the post-noon plasmasphere to form the poleward-streaming plumes of enhanced plasma density. C. N. Mitchell et al. (GPS TEC and scintillation measurements from the polar ionosphere during the October 2003 storm, submitted to *Geophysical Research Letters*, 2005) studied the polar ionosphere using GPS TEC and scintillation measurements and found that the plasma scintillation to be co-located with the steep gradients in TEC. It is postulated that the plasma irregularities associated with scintillation may have originated in the mid latitudes and been transported by plasma convection into the polar region. *Basu et al.* [2005] analyzed amplitude scintillation of satellite signals at 250 MHz and the Defense Meteorological Satellite Program (DMSP) data to explore the evolution of ionospheric plasma density structures at middle and equatorial latitudes during the October 29–31 magnetic storms. They found that the onset of equatorial scintillation was delayed from that at mid-latitudes by ~20 minutes, attributable to the instantaneous electric field penetration and plasma instability growth time of equatorial irregularities.

[9] The severity of the October geomagnetic storms marked by the day-time aurora reported in Boston in response to the 30 October 2003 storm [*Pallamraju and Chakrabarti*, 2005]. High spectral resolution measurements of OI 6300 Å emissions revealed a sixfold enhancement over the normal daytime emission rates. *Chi et al.* [2005] reported extraordinary density enhancements in both the magnetosphere and ionosphere coinciding with intervals of southward IMF and high-speed solar wind, demonstrating how the eastward electric field imposed on the ionosphere is related to the dense plasmaspheric drainage plume. W. Li et al. (Plasma sheet formation during long period of northward IMF, submitted to *Geophysical Research Letters*, 2005) simulated the cold dense plasma sheet (CDPS) event observed on October 23, 2003, by the Cluster spacecraft using open GGCM MHD and found that the capture of magnetosheath plasma is sufficient to produce a cold dense plasma sheet.

5. Heliospheric Consequences

[10] *Richardson et al.* [2005] used an 1D MHD model to propagate observations near 1 AU to more distant spacecraft (Ulysses, Cassini, Voyager 2, Voyager 1) and determine if a global merged interaction region (GMIR) was formed by the Oct–Nov 2003 events. By comparing the model with observations at the distant spacecraft, they found that the shocks observed at 1 AU, Cassini, and Voyager 2 are consistent with a single large ICME. Ulysses, on the other side of the heliosphere, observed related disturbances, but from a different ICME. On the other hand, no shock signatures were observed by Voyager 1, suggesting that the shock front was not a global signature, and that a GMIR did not form. The lack of GMIR formation from these extreme events at 1 AU suggests that truly global GMIRs may be quite rare structures. GMIRs are thought to be

important for the modulation of galactic cosmic rays (GCRs). If they are rare, then one has to consider other structures such as high-latitude CMEs to explain the GCR modulation. Another implication is that the heliospheric radio emission may have a localized non-GMIR source. *Burlaga et al.* [2005] report observations by Voyager 2, at 73 AU, of the transient flow system observed near the Earth from Oct 24 to Nov 7, 2003. By the time the disturbance reached Voyager 2, ~180 days after leaving the Sun, the multiple events observed at 1 AU had formed a single merged interaction region (MIR). The MIR was associated with an unusually large (~450 days) and fast (~560 km/s) stream following a forward shock, with a sheath-like region between the shock and the stream. The MIR was associated with a large decrease in cosmic ray intensity, lasting more than 70 days. A large increase in the flux of 2.5 MeV protons was observed beginning 17 days prior to the shock. It is interesting that the signatures at 73 AU were relatively simple, given the extremely complex nature of the events at 1 AU.

[11] *Munakata et al.* [2005] use observations from a ground-based cosmic ray muon hodoscope to study the directional anisotropy of cosmic rays in a large Forbush Decrease observed on Oct. 29, 2003. Since cosmic rays have such high speeds, the anisotropy was observed ~7 h prior to the arrival of the shock at Earth, providing a precursor signature for large shocks. Comparison with the theory of these precursors allows the authors to calculate the shock normal angle, $\theta_{Bn} = 6°$. This result is in contrast to the value $\theta_{Bn} = 60°$ obtained from in situ measurements, perhaps due to complications resulting from the multiple shocks present at this time, or to complicated shock geometry. The authors also find that the precursor lead-time is independent of rigidity, suggesting that this signature could be observed by either muon or neutron monitors.

6. Summary and Conclusions

[12] The results highlighted in this paper provide a glimpse of the extensive and global nature of the violent Sun-Earth connection events of 2003 October–November. Although it is not unusual that such solar eruptions occur during the declining phase of a solar cycle, these events bench mark the level of understanding we have on the behavior of the sun over different time scales. Understanding these events will help us assess the extremeness in terms of the free energy available at the Sun and the geospace and heliospheric consequences.

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